

Argonne National Laboratory

A ZONED LOADING FOR A ZPR-III-TYPE FACILITY

by

A. G. Edwards

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ANALYSIS OF THE RESEARCH AND DEVELOPMENT PROGRAMS

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A ZONED LOADING FOR A ZPR-III-TYPE FACILITY

by

A. G. Edwards

ABSTRACT

A series of calculations, centered around a possible zoned critical in a ZPR-III-type machine, is presented and discussed. Criteria of selection for equivalent samples and optimum drivers are discussed. The conclusion is drawn that measurements on a combination of one or more zoned criticals, and the careful computation of correction terms, can yield nearly all the experimental data which might be derived from a full-scale, all-sample critical without significant loss of accuracy. The major exception is an experimental value for critical mass.

I. INTRODUCTION

The checking of reactor calculations by experimentation with zero-energy critical facilities is a standard practice. When interest is with a particular power reactor, this is simulated as far as possible in a zero-energy facility, but when the interest is more broadly based, the zero-energy reactors built are geometrically simple and have two regions only, namely, core and blanket, so that interpretation is as simple as possible.

In accordance with this philosophy, a wide range of different simple cores have been built in the ZPR-III assembly machine, and detailed attempts have been made to mockup the Enrico Fermi reactor, the EBR-II reactor, and RAPSODIE. Similarly, ZEUS and its variants served as a simulant for the then conceptual Dounreay Fast Reactor.

Conceptual plutonium-fueled power reactors with inventories in excess of a ton are of interest. However, at present the plutonium immediately available for zero-energy experiments does not exceed about 220 kg for the ZPR-III assembly and smaller amounts for ZEBRA and VERA. Three methods are possible for obtaining relevant experimental information in these circumstances: (i) build a fast exponential, (ii) build a plutonium-fueled assembly with a noncapturing diluent which has a degraded spectrum without a large critical mass, and (iii) build a two-part core, involving both U^{235} and plutonium, either homogeneously distributed or separated out into different zones.

Hess and Gasidlo⁽¹⁾ have recently described the ZPR-III Assembly 41, with composition similar to that of the fast exponential described by Beyer⁽²⁾ and to the fast part of the coupled fast-thermal system described by Hummel et al.⁽³⁾ Hess and Gasidlo compared the results with the same reactor composition and concluded that, although the exponential gave reasonable values of fission ratios and buckling, inferences about critical mass from buckling and reflector savings gave very poor accuracy. The fast-thermal critical assembly was found to give fairly good agreement with the all-fast critical for central fission ratios and reactivity effects, though these would have been improved by the use of a fast rather than a thermal driver. Inferences about critical mass from a knowledge of spectral indices and reactivity effects are difficult to make, and the knowledge of these quantities should be as accurate as possible.

The AETR Critical Experiments

An intensive exploration of the zoned critical technique has been made by the Atomics International (AI) group concerned with the Advanced Epithermal Thorium Reactor (AETR) concept.⁽⁴⁾ The potential of the AETR concept depends critically on the nuclear parameters of U^{233} and thorium in the epithermal region of the spectrum, where they were not well known, and a zero-energy critical should be built to check on the data. There were only 25 kg of U^{233} available to check data for predictions of a large power reactor involving a ton or more of U^{233} . The U^{233} is distributed through a test region the size of which is determined by the amount of U^{233} available, and which reproduces the composition of the conceptual reactor of interest. This is surrounded by a buffer region fueled by U^{235} and thorium, separated by a thorium decoupler from the thermal driver, which consisted of U^{235} and polyethylene. The whole was surrounded by a polyethylene reflector.

The reasoning behind the experimental design and the proposed form of analysis are described by Campise,⁽⁵⁾ who gives three conditions to be met if the zoned arrangement is to be well designed. These are met by matching flux and adjoint spectra at the sample center with those at the center of the conceptual reactor, and using a sample composition which is the same as that of the conceptual reactor.

The difficulties of analysis designed to improve cross-section information are those general to fast integral experiments, somewhat accentuated by the zoned arrangement. These difficulties and Campise's proposed solution of them may be illustrated by reference to, say, the treatment of a measured one-group fission cross section for a reactor constituent. We derive a quantity ΔF from experiment and multigroup calculation, where

$$\Delta F = F(\text{experiment}) - F(\text{calculation})$$

$$\approx \sum_i \phi_i \delta \sigma_i + \sigma_i \delta \phi_i,$$

where $\delta\sigma_i$ is the uncertainty in the cross section and $\delta\phi_i$ is the uncertainty in the flux which stems from it.

Assume that an iterative approach is permissible in which, in the first place, we can write $\delta\phi_i = 0$. In order to solve for $\delta\sigma_i$ with the single experimental number $\Delta\sigma$, the calculated quantities $\partial F/\partial\sigma_i$ are used to spread the observed discrepancy amongst the several groups. In one form this amounts to the assumption that each of the multigroup cross sections is equally in error, which is rather restrictive.

In a series of seven AI experiments, several compositions of test region were used, having mean neutron energies of 422 keV, 140 keV, 120 keV, 66 keV, 5.5 keV, 9.9 eV, and ~ 7 eV. Experimental measurements were made of fission ratios at the sample center, the worths of different neutron sources, and the worths of various fissile, fertile, and inert materials.

Helm⁽⁶⁾ has examined fast reactor zoned critical techniques by means of two-group approach. He considers, for example, two homogeneous, finite, cylindrical reactors of the same radius, and the composite reactor formed by bringing together half of each to give an arrangement which, on a one-group argument, is also just-critical. As might be expected, it remains critical on a two-group basis only if certain spectrum-matching criteria are met by the two compositions. A one-group argument also suggests that if a finite critical reactor of radius R is split at its midplane, and an arbitrary length of another reactor of radius R is introduced, the arrangement will remain critical provided the new material is critical in an infinite cylinder of radius R . A two-group analysis again imposes spectrum-matching conditions for this to be true. The first arrangement requires 50% of the material required for a full critical; the second method less, but with the proviso that the thinner the sample slice, the less accurate the experiment.

Meneghetti and Ishikawa⁽⁷⁾ have considered the problems of mixed plutonium-uranium cores in a study in which the 5 v/o fissile material, in a reactor of otherwise fixed composition, is made up of U^{235} and of Pu^{239} in varying proportions. Their calculations resulted in a fissile material loading ranging from 2000 kg in the all- U^{235} case to 400 kg in the all- Pu^{239} case. The basic calculations (done with four groups) was to change one of the input cross sections for plutonium and to determine, as a function of plutonium composition, the resultant change in buckling. It was assumed that an errorless measurement is made of the buckling of the system containing fissile material, which is 10% Pu^{239} -90% U^{235} , and that discrepancies between experiment and calculation can be attributed solely to one plutonium cross section. It was shown that this error is linearly dependent on plutonium content. Extrapolation then gave a correction term and a reduced error for the predicted buckling of the all-plutonium-fueled assembly. The plutonium necessary was about 38% of that required for the analogous plutonium-fueled assembly.

They also considered the alternative arrangements in which the plutonium and U^{235} are separated into different zones. If, for example, the central 10% of the composite system is plutonium-fueled, the percentage error in predicted radius for the zoned arrangement is about half the percentage error in the all-plutonium critical, if that error stems solely from an incorrect value for the plutonium $\nu\sigma_f$.

Whilst these numbers make the method look attractive, the assumptions that there is only one cross section in error and that this is known, are restricting ones.

In some earlier work by the author⁽⁸⁾ a similar approach to that adopted below was used, but without the specific bias towards ZPR-III-type assemblies. The general question is there discussed of the value in assessing plutonium data of both zoned experiments and few-component experiments in which the spectrum is softened by the use of noncapturing diluents. They are found to be complementary rather than alternative.

II. SOME GENERAL CONSIDERATIONS

If we were unrestricted in plutonium inventory, the critical assembly built would be used to make the following measurements: (i) critical mass; (ii) worths of different materials as a function of position; (iii) reaction rates of different materials as a function of position; (iv) Rossi- α . The ultimate objective of a zoned critical arrangement, therefore, is to yield an experimental measurement of just these numbers. Work so far has concentrated on sample regions centrally placed within a driver region, but this is restrictive, and in general, the sample region may be considered to be anywhere. We then have the basic requirement of a zoned critical that the experimental uncertainty in the measurement shall not be swamped by the computational uncertainty in going from the zoned critical to the equivalent point in the all-sample critical. Ideally, the calculated correction is effectively zero.

This requirement can be clarified by writing down expressions for some of the quantities it is required to measure, using a multigroup flux representation.

The reaction rate is given by $\sum_{i=1}^N \phi_i \sigma_i$, where N is the number of groups, and the requirement, (Reaction Rate) zoned system = (Reaction Rate) sample system for sufficient different materials implies adequate matching of the real spectra in the two systems, but lays no restriction on the adjoint spectra. On the other hand, with perturbation effects or danger-coefficient measurements, both adjoint and real spectra are involved.

They also considered the alternative arrangements in which the photonium and U^{235} are separated into different zones. If, for example, the central 10% of the composite system is photonium-filled, the percentage error in predicted values for the zoned arrangement is about half the percentage error in the all-photonium critical. It thus error arises solely from an incorrect value for the photonium ρ .

Whilst these numbers make the method look attractive, the authors know that there is only one source section in error and that this is known. Are restricting areas?

In some earlier work by the author (8) a similar approach to that adopted below was used, but without the specific bias towards BPR III-type assemblies. The general question is: how does the value of the zoned arrangement differ from that of the all-photonium arrangement? The experiments in which the question is asked by the use of non-predicting elements. They are found to be complementary rather than alternative.

II. SOME GENERAL CONSIDERATIONS

It was mentioned in photonium inventory, the critical assembly built would be used to make the following measurements: (i) critical mass; (ii) worth of different materials as a function of position; (iii) reaction rates of different materials as a function of position; (iv) k_{eff} . The estimate objective of a zoned critical arrangement, therefore, is to yield an experimental measurement of k_{eff} in the zoned arrangement. Work in this connection as an example: regions - essentially all of which are known to be restricted, and in general, the same region may be considered to be equivalent. We then have the basic requirement of a zoned critical, that the experimental uncertainty in k_{eff} from the zoned critical to the equivalent point in the all-photonium critical. Ideally, the calculated correction is effectively zero.

The requirement can be clarified by writing down expressions for some of the quantities it is required to measure, using a simplified representation.

The reaction rate is given by $R = \frac{1}{V} \int \rho \phi dV$, where ρ is the number of

groups, and the requirement (Reaction Rate) zoned system is: Reaction Rate sample system for sufficient different materials having adequate matching of the test spectra to the ρ spectrum, but with no restriction on the adjacent spectra. On the other hand, with partitioned effects or design conditions measurements, both adjacent and test spectra are involved.

If the zoned critical has the same dimensions as the all-sample critical, the meaning of "equivalent position" is straightforward. Now the physical size of a system can always be increased without changing the spectral characteristics by reduction of the density, so that size and spectral matching are independent, provided the full-density buckling of the driver is greater than that of the sample.

The ideal driver to be used in conjunction with a given sample, therefore, has the following properties:

- (i) It has a larger buckling than the sample.
- (ii) Its real spectrum is the same as that of the sample.
- (iii) Its adjoint spectrum is the same as that of the sample, together with the requirement in a practical case.
- (iv) The resultant zoned critical is within the inventory and composition restrictions of the experimental facility.

There is a further pertinent consideration affecting calculations of zoned critical systems. Calculation may be used to show the degree of match between a driver and a sample mixture, but by basic assumption, those calculations can only be made by use of imperfect input data and techniques. It is desirable to show, in some way, that these imperfections do not rob the calculations of their value in showing that the basic requirements of zoned critical design are met. The only thing that can be done in this direction is to repeat the calculations with different cross-section libraries and to show that the essential comparisons remain unaltered.

A calculation series based on the above ideas is described below, where the 16-group Roach⁽⁹⁾ data (Library 700) and the 16-group Yiftah⁽¹⁰⁾ data as modified by Davey⁽¹¹⁾ (Library 635) are employed.

III. THE REFERENCE MIXTURE

The present calculations presuppose some plutonium-fueled oxide reactor composition which is of prime interest and is to be studied experimentally in a ZPR-III-type assembly. First, therefore, the composition of the basic reactor as specified is taken; next, an equivalent sample mixture is concocted which experimentally is conveniently equivalent to it. In the present case, convenience is weighted rather more heavily than exact equivalence. Finally, a suitable driver is selected and some calculations made on a composite system.

The composition of the reference reactor used in the present study is shown in Table I; it is basically an oxide-fueled reactor with 25 v/o structure, 36.4 v/o sodium, 30.8 v/o fuel, and 7.8 v/o void, using plutonium

of a fairly large content of Pu^{240} . The blanket composition selected is a compromise between the compositions of radial and axial blankets which might be used in an actual cylindrical reactor. Certain information about a spherical version of such a reactor is also given in Table I.

Table I

PROPERTIES OF REFERENCE REACTOR

A. Composition

Blanket		Core	
Material	v/o	Material	v/o
U^{238}	24.82	Pu^{239}	1.974
U^{235}	0.18	Pu^{240}	0.3901
Fe	25.00	U^{238}	12.994
Na	30.00	U^{235}	0.0935
C	10.00	Fe	25.00
		Na	36.40
		O	15.452

B. Properties

DSN S4 Calculation - Library 635

Spherical Geometry Blanket thickness = 50 cm
 Critical Radius 71.7 cm
 Critical Volume 1540 liters
 Critical Mass Pu^{239} 580 kg

	Regular	Adjoint
$\sum_1^n (\phi_i^A - \phi_i^B)^2 =$	1.6	0.25
$\sum \left(\frac{\phi_i^A - \phi_i^B}{\phi_i^A + \phi_i^B} \right) =$	0.02	0.0023

Group	(A) Central Flux (Regular)	(B) Fundamental Mode	(C) Central Flux (Adjoint)	(D) Fundamental Mode
1	1.32	1.35	8.44	8.40
2	2.79	2.80	8.36	8.21
3	4.88	4.83	7.81	7.72
4	7.12	7.21	6.90	6.84
5	10.90	10.99	6.72	6.64
6	12.75	11.77	6.53	6.48
7	13.56	13.66	6.31	6.26
8	12.10	11.97	6.13	6.10
9	9.17	9.50	6.04	5.99
10	8.09	8.15	5.89	5.86
11	4.88	5.37	5.71	5.70
12	5.43	5.02	5.53	5.54
13	2.93	2.90	5.24	5.28
14	1.68	1.75	4.94	5.02
15	1.61	1.72	4.74	4.83
16	0.80	1.03	4.72	5.15

For survey purposes, the results of calculations of spectral properties of mixtures obtained with the fundamental-mode approximation programmed for the IBM 1620 computer are presented. For comparing spectra, particularly for putting spectra in an order of excellence according to their closeness of match to a standard, it is necessary to characterize a spectrum by a single number.

The effective one-group cross section for any of the common nuclides might be used for this purpose, but some criterion divorced from the nuclear parameters of any one material is considered superior. Two mismatch criteria are employed here, defined as follows: The mismatch between two regular or adjoint spectra $\phi_1 \rightarrow \phi_n$ and $\phi'_1 \rightarrow \phi'_n$ is given by either

$$M_1 = \sum_1^n (\phi_i - \phi'_i)^2$$

or

$$M_2 = \sum_1^n \left(\frac{\phi_i - \phi'_i}{\phi_i + \phi'_i} \right)^2$$

where

$$\sum_1^n \phi_i = \sum_1^n \phi'_i = 100.$$

A more general form of mismatch criterion would include weighting factors W_i multiplying each of the flux difference terms $(\phi_i - \phi'_i)$. If good match in a particular part of the spectrum is then of principal interest, the corresponding W_i would be given appropriately large values.

In Table I the mismatch between the fundamental mode and DSN calculated central spectra are shown to be small compared with mismatch between driver and sample spectra discussed later, both for adjoint and regular fluxes. It is concluded, therefore, that in the present context, the fundamental-mode calculation yields an adequate representation of central spectra.

IV. THE SAMPLE MIXTURE

The sample mixture is that mixture which is actually assembled in the zero-energy reactor, and hence it must have the following properties:

(i) The plutonium has a 5% Pu^{240} content.

(ii) The mixture must be assembled from plates of different materials with a recurring pattern of a relatively small number of units.

The facts that oxygen must probably be introduced as iron oxide, and that sodium and plutonium carry with them appreciable amounts of canning, impose further limitations. In the present case, a cell was assumed to consist of 16 standard (1/8-in.) columns. Approximate figures were taken for the volume percent of different constituents corresponding to a range of different, physically realizable reactor compositions; their fundamental-mode spectra were calculated and compared with those of the reference reactor in terms of the comparison criteria M_1 and M_2 . The compositions used are given in Table II, and the results in Table III. In view of the fact that the compositions using canned materials vary with the size of the cans, precise figures cannot be given without specifying a detailed loading.

Table II

THE COMPOSITIONS OF VARIOUS SAMPLE MIXTURES
(Atoms per cc $\times 10^{-23}$)

No.	Pu^{239}	Pu^{240}	U^{238}	U^{235}	Fe	Na	O	C
3001	1* 0.009888	0.000518	3** 0.075024	0.000540	0.263840	7† 0.057981	5†† 0.134400	
3002	1 0.009888	0.000518	4 0.100032	0.00072	0.25241	6 0.049698	5 0.1344	
3004	1 0.009888	0.000518	3 0.075024	0.00054	0.19354	9 0.074547		3 0.13198
3005	1 0.009888	0.000518	2 0.050016	0.00036	0.27528	8 0.066264	5 0.1344	

*Number of plutonium columns containing about 5% Pu^{240} .

**Number of natural uranium columns.

†Number of columns of canned sodium.

††Number of columns of iron oxide.

Table III

THE MATCHING OF REFERENCE AND SAMPLE COMPOSITIONS

Criterion	Library	3001	3002	3004	3005
M_1	635	1.66	4.38	8.54	0.58
Regular	Roach	4.60	16.94	4.08	0.76
M_1	635	0.13	2.64	0.14	1.88
Adjoint	Roach	3.37	7.10	3.87	3.67
M_2	635	0.034	0.154	0.04	0.011
Regular	Roach	0.112	1.06	0.74	1.03
M_2	635	$7.82 \bar{4}$	$1.64 \bar{2}$	$8.13 \bar{4}$	$1.74 \bar{2}$
Adjoint	Roach	0.037	0.070	0.043	0.035

On the basis of these numbers, No. 3005 was chosen as the optimum sample mixture. It is noteworthy that the order of excellence depends on both library and comparison criteria, and markedly on whether real or adjoint fluxes are considered. The use of the M_2 criterion gives equal weighting to all fluxes, and perhaps is very unsuitable for the Roach calculations where so little flux lies in the lower groups. It was included as an index emphasizing the low-energy part of the spectrum, since this is important in calculating the magnitude of the Doppler effect.

V. THE COMPOSITION OF THE DRIVER

The general method of selecting a suitable driver is an extension of that outlined in the previous section. The reference mixture plays no further part in the study, and comparison criteria are between the sample and possible uranium-fueled drivers, the argument being that an ability to calculate sample-mixture properties implies an ability to calculate properties of the reference mixture. Difficulties associated with the near absence of Pu^{240} from the sample are inescapable.

For reasons discussed later, the driver must have a larger buckling than the sample, and this implies that its U^{238} content must be low. The absence of this fission-threshold material means that adjoint matches are inevitably poor, since in the driver mixture there is no mechanism to give high-energy neutrons an increased importance.

Some of the driver compositions studied are given in Table IV and their degree of mismatch to the sample spectrum is given in Table V. Mixture No. 2060 was selected for the driver composition. The one-group cross-section values for the mixture are compared with those for sample and reference in Table VI, where large differences may be noted for the B^{10} (α) cross section despite the rather careful matching process.

Table IV
COMPOSITIONS OF DRIVER MIXTURES
(Columns and atoms/cc $\times 10^{-23}$)

No.	U^{235}	U^{238}	Fe	C	Al	K^2 Lib. 635 Lib. 700	No.	U^{235}	U^{238}	Fe	C	Al	K^2 Lib. 635 Lib. 700
2009	1 0.02345	0.001766	8 0.4320	7 0.3080		0.003389 0.003675	2031	1 0.02345	0.001766	4 0.1760	11 0.3482		0.002433 0.002681
2010	1 0.02345	0.001766	6 0.3430	9 0.3960		0.003620 0.003957	2032	1 0.02345	0.001766	8 0.3520	7 0.2216		0.002991
2014	1 0.02345	0.001766	10 0.5209	5 0.2200		0.003124 0.003350	2060	1 0.02365	0.02679	10 0.5209	4 0.1760		0.002879 0.002988
2015	1 0.02345	0.001766	12 0.6908	3 0.1320		0.002833 0.002990	2061	1 0.02383	0.05181	9 0.4764	4 0.1760		0.002772 0.002828
2016	1 0.02345	0.001766	14 0.6988	1 0.0440		0.002525	2062	1 0.02383	0.05181	10 0.5209	3 0.1320		0.002656 0.002699
2020	2 0.0469	0.003533	0.07623		14 0.4432	0.004046 0.004151	2063	1 0.02401	0.07683	10 0.5209	2 0.08799		0.002451 0.002445
2030	1 0.02345	0.001766	0.07623		15 0.4749	0.001945 0.002051	2064	1 0.02401	0.07683	9 0.4764	3 0.1320		0.002555 0.002562

Note: K^2 in this table is calculated for an iron diluent; but for comparison purposes, cross sections for a stainless steel diluent were employed with the 635 Library.

Table V

COMPARISON OF SAMPLE MIXTURE WITH VARIOUS DRIVER MIXTURES

Order	$\sum (\phi_i - \phi_i^*)^2$		$\sum \frac{(\phi_i - \phi_i^*)^2}{(\phi_i + \phi_i^*)^2}$		$\sum (\phi_i^* - \phi_i^{*'})^2$		$\sum \frac{(\phi_i - \phi_i^{*'})^2}{(\phi_i + \phi_i^{*'})^2}$	
Library 635								
1	2014	27	2014	0.131	2063	11.4	2063	0.073
2	2061	28	<u>2060</u>	0.22	2062	18.3	2062	0.115
3	<u>2060</u>	29	2009	0.24	2061	18.4	2061	0.115
4	2009	34	2015	0.27	<u>2060</u>	28.2	<u>2060</u>	0.177
5	2015	36	2061	0.34	2030	33.0	2030	0.193
6	2062	39	2010	0.44	2031	37.8	2020	0.230
7	2010	54	2032	0.47	2020	38.1	2031	0.235
8	2031	56	2062	0.58	2016	41.4	2016	0.260
Library 700								
1	2061	59.4	2014	1.79	<u>2060</u>	37.6	<u>2060</u>	0.255
2	<u>2060</u>	64.2	2015	1.95	2030	39.3	2014	0.290
3	2014	72.3	2009	2.32	2015	38.7	2015	0.281
4	2062	79.9	2010	3.04	2014	39.5	2030	0.284
5	2009	84.2	<u>2060</u>	3.18	2020	40.0	2020	0.295
6	2064	87.2	2030	4.82	2009	40.5	2009	0.301
7	2015	87.7	2061	5.56	2031	40.7	2031	0.304
8	2010	112.8	2062	6.48	2010	41.7	2010	0.313

Table VI

COMPARISON OF ONE-GROUP CROSS SECTIONS FOR REFERENCE,
SAMPLE, AND DRIVER MIXTURES
(Spectra Based on Fundamental-mode Calculation)

	Pu ²³⁹ nf*		U ²³⁸ nf		U ²³⁵ nf**		B ¹⁰ nα		U ²³⁸ nγ		Pu ²⁴⁰ nf	
Reference	1.92	2.03	0.047	0.051	1.87	2.20	1.83	0.557 [†]	0.266	0.30	0.355	0.354
3005	1.93	2.03	0.046	0.050	1.87	2.20	1.83	0.558 [†]	0.267	0.30	0.359	0.361
2060	1.89	1.90	0.056	0.063	1.74	1.86	1.56	0.396 [†]	0.235	0.282	0.443	0.469

(Left-hand Column: 635 Library; Right-hand Column: Roach Library)

*Unshielded data.

**Barns/atom = 570 in Roach case only.

[†]Natural boron.

VI. THE USE OF A FILTER

In his survey calculations for the design of ZPR Assemblies 42 and 43, G. Fischer⁽¹²⁾ studied the effect of filters between the driver and the sample regions. Filters were also used in the AETR criticals. These filters are thin regions of, for example, U²³⁸ or U²³⁸ mixed with carbon, the function of which is to improve the spectral match between driver and sample.

Some study was made of filters in the present case in the following way. An infinite reflected cylindrical reactor with the composition of the

sample mixture was calculated by means of the DSN code and the 635 Library in 16 groups. In order that the infinite reactor should be critical when its radius approximated the radius of the finite reactor, a fictitious absorbing material "fictitium" was distributed throughout the core, and the concentration of this was varied to make the system critical with the infinite cylinder radius equal to the finite cylinder radius. The cross sections are zero except for capture, and this is given by:

$$\Sigma_{c_i} = \beta^2/3 \Sigma_{tr_i},$$

where β^2 is the buckling of the core material and Σ_{tr} is the macroscopic transport cross section. A series of other calculations were performed in which the uniform cylindrical core was replaced, first, by one with two zones corresponding to sample material and driver, and then by one with three zones corresponding to sample filter and driver. The principal filters studied were 2 in. thick, and consisted of U^{238} and carbon mixed in different proportions. The core radius of the infinite cylinder was held constant, and the fictitium concentration varied in each case to make the system critical. The precise method of making this correction can be varied, but this is unlikely to affect the general conclusion drawn from the results.

The results are shown schematically in Figs. 1 and 2, where spectral mismatch at central and eccentric positions are shown, respectively. At each point the flux is normalized to 100 for all the systems calculated, and $\phi_i - \phi_i'$ is plotted against group number, where ϕ_i is the spectrum corresponding to the all-sample cylinder, and ϕ_i' is the spectrum in each of the various zoned and filtered assemblies. The result is a pictorial indication of how filtering improves the closeness of match in a zoned critical assembly.

In Table VII, the effect on spectrum mismatch of filtering is shown in terms of the same criteria as were used earlier. A part of the same data is shown in another way by tabulating a selection of one-group cross sections at an eccentric point for the standard arrangement, a zoned arrangement with no filter, and a zoned arrangement with a filter consisting of 1/2 in. carbon and 1-1/2 in. of U^{238} .

A filter is of some value in improving spectral match. However, it is not used in the present series of calculations since it is an undoubted complication in theory and experiment, and the spectral match is fairly good without it.

Table VII

THE INFLUENCE OF A FILTER IN IMPROVING SPECTRAL MATCH
(635 Library Calculations)

Filter	Central (R = 3.2 cm)		Eccentric (R = 26.4 cm)	
	M ₁	M ₂	M ₁	M ₂
None	0.24	0.0056	3.7	0.045
1/2 in. U ²³⁸	0.12	0.0032	3.5	0.089
1 in. U ²³⁸	0.12	0.0027	3.8	0.10
2 in. U ²³⁸	0.15	0.0017	4.5	0.13
1-1/2 in. C; 1/2 in. U ²³⁸	0.17	0.0059	6.3	0.19
1 in. C; 1 in. U ²³⁸	0.046	0.0016	4.7	0.038
1/2 in. C; 1-1/2 in. U ²³⁸	0.044	0.00033	1.0	0.028

Filter	One-group Cross Sections (b) at R = 26.4 cm					
	U ²³⁸ nf	Pu ²⁴⁰ nf	Pu ²³⁹ nf	U ²³⁵ nf	U ²³⁸ nγ	B ¹⁰ nα
None	0.0477	0.380	1.896	1.789	0.247	1.860
1/2 in. C; 1-1/2 in. U ²³⁸	0.0413	0.339	1.906	1.836	0.259	1.796
Standard	0.0458	0.356	1.919	1.851	0.262	1.806

VII. ILLUSTRATIVE 16-GROUP CALCULATIONS
IN SPHERICAL GEOMETRY (DSN)

Now that an "equivalent sample" and an optimum driver have been defined, and the decision has been taken not to use a filter, spherical calculations can be used to explore the properties of the zoned critical. The object of these is principally to furnish a standard of comparison for subsequent two-dimensional, 5-group diffusion theory calculations using CRAM.

The configurations involved in the calculations made are shown in Fig. 3, and Table VIII gives the compositions of the various zones. Calculation results are shown in Table IX.

The properties of a critical sphere of the sample material were first calculated (Case I). A blanket was selected with a composition generally similar to that of a power reactor, with low-density aluminum substituted for sodium, which is a convenient, even though not too exact, replacement in zero-power mockups.

Next, calculations were made for a reactor with the composition of the preferred driver (mixture No. 2060, Table IV), and the density was varied to make the reactor critical in the same volume as the previous case. This is Case II.

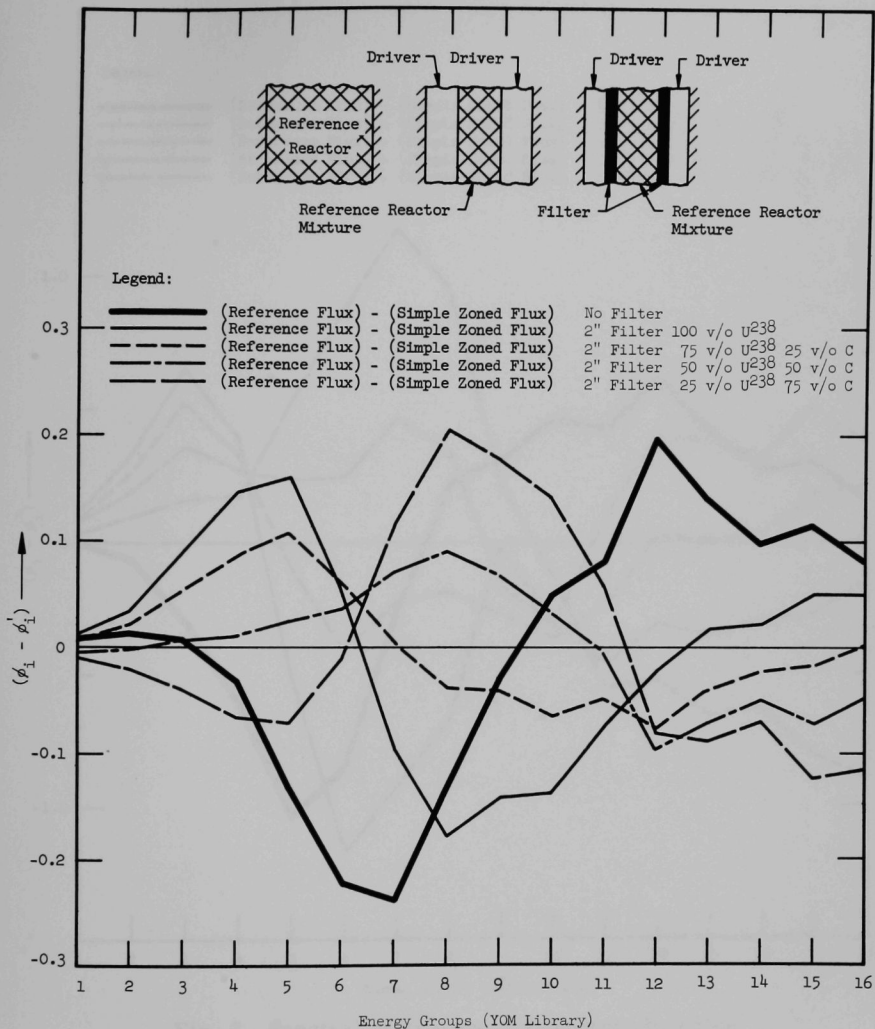


Fig. 1. Spectral Mismatch at Core Center

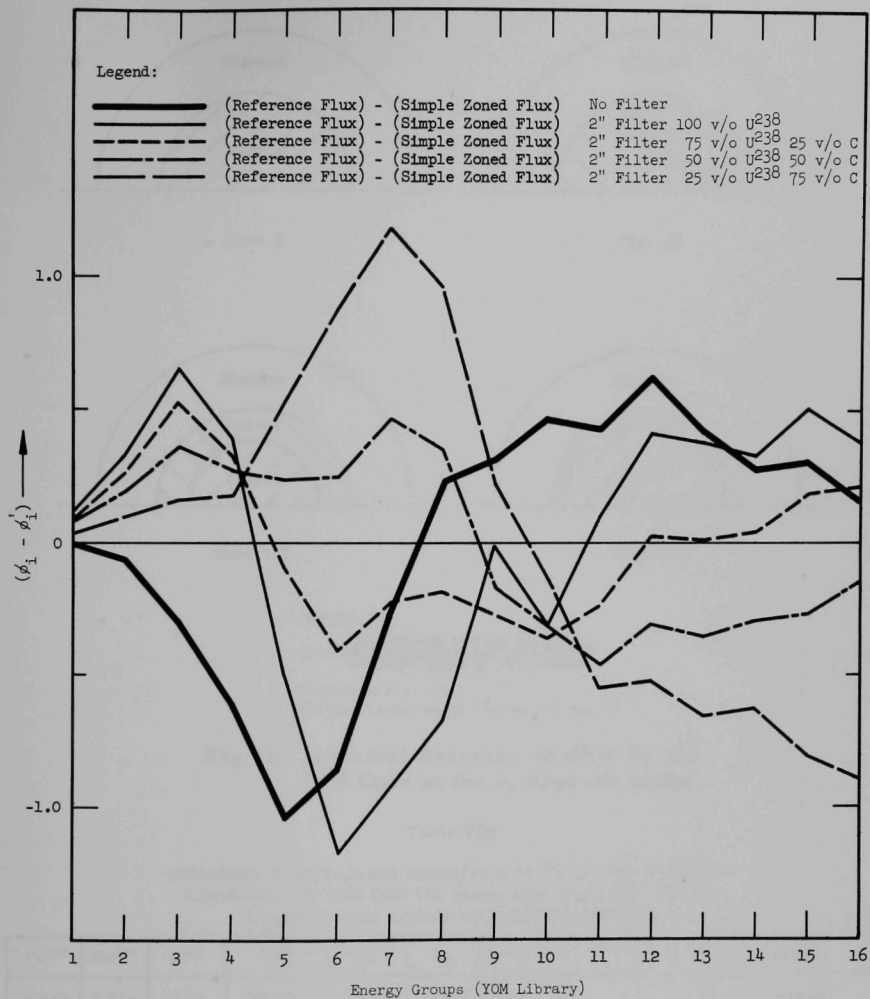
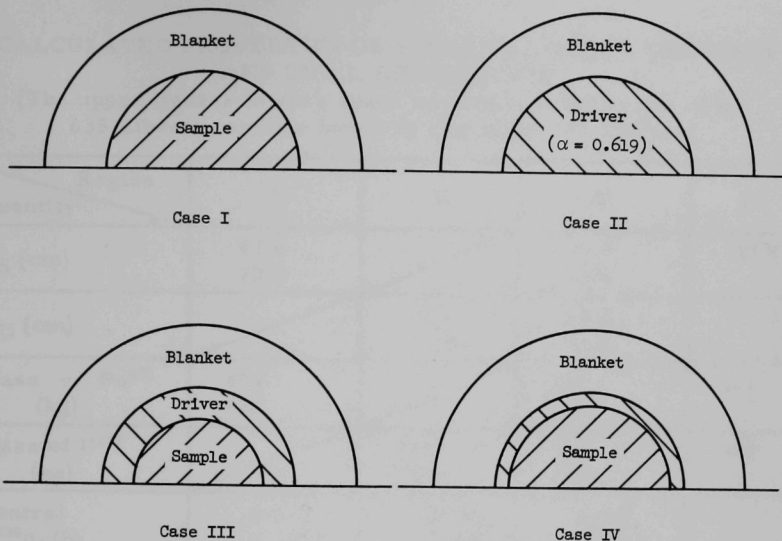


Fig. 2. Spectral Mismatch at Eccentric Position



Notes:

$$\alpha = \frac{\text{Density of Driver as Used}}{\text{Maximum Density Obtainable}}$$

Dimensions in cm

Compositions as in Tables II and IV

Fig. 3. Spherical Reactors Studied by the DSN Code in the S_4 Approximation

Table VIII

COMPOSITIONS (v/o and atoms/cc $\times 10^{-20}$) IN THE VARIOUS REGIONS FOR THE DSN (16-group spherical) AND CRAM (5-group finite cylindrical) CALCULATIONS

Pu ²³⁹	Pu ²⁴⁰	U ²³⁵	U ²³⁸	Fe	Na	O	C	Al	Region
9.888	0.518	0.36	50.0016	275.28	6.626	134.4			Sample (Mixture No. 3005) Table II
2.06	0.108	0.075	10.42*	32.5	30.12	14.00			
		23.65	26.789	520.9			173.88		Driver (Mixture No. 2060) Table IV
		4.927	5.581	61.5			21.0		
		1.08	150.12	262.57				85.63	Blanket
		0.225	31.275	31.0				14.2	

*10.32 v/o in CRAM cases (49.526×10^{20} atoms/cc).

Table IX

CALCULATED PROPERTIES OF SPHERICAL ZONED CRITICALS AND THEIR EQUIVALENTS

(The upper figures in each space were calculated by use of the
635 Library, and the lower by use of the 700 Library)

Region Quantity	I	II	III	IV
R_S (cm)	67.0 70.9		47.0 47.0	47.0
R_D (cm)		67.0 70.9	67.5 71.7	57.1
Mass of Pu^{239} (kg)	494 586		171 171	171
Mass of U^{235} (kg)		720 779	488 580	320
Central $U^{238}\sigma_f$ (b)	0.046 0.0503	0.056 0.063	0.046 0.0502	
$Pu^{239}\sigma_f$ (b)	1.92 2.03	1.88 1.90	1.91 2.03	
$B^{10}(n\alpha)(b)$ $B_{nat}(n\alpha)(b)$	1.80 0.558	1.55 0.398	1.78 0.554	

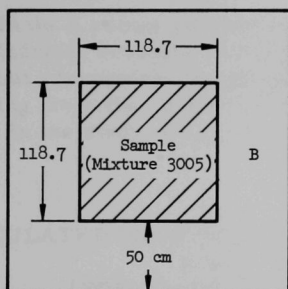
The zoned system, Case III, was taken to have a central sample region whose size is such that the available plutonium is used, and a driver whose composition is that given by Calculation II, the radius being adjusted to attain criticality. As might be expected, the final radius for the core was rather similar to that for the first two cases.

Finally, a case (Case IV) was studied in which a driver at full density was used. This reduces the U^{235} inventory and has only a small effect on the central spectrum, but its use precludes the possibility of measuring quantities at eccentric positions. Any serious disparity in size and shape between the zoned critical and the "all-sample" critical means that unless the sample is centrally placed, it is impossible to relate its center point to an equivalent position in the all-sample critical.

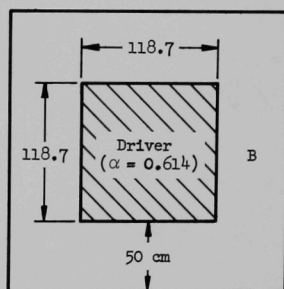
VIII. FIVE-GROUP CALCULATIONS IN CYLINDRICAL GEOMETRY (GRAM)

The preferred geometry of experimentation is cylindrical or quasi-cylindrical, and two-dimensional codes are necessary to study examples of

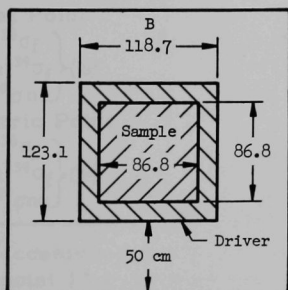
this type. The four basic cases are shown in Fig. 4. Case VI is the equivalent of Case I, i.e., a blanketed right circular equilateral cylinder of sample material. Similarly, Case VII corresponds to Case II, the density of the driver being varied until it is critical when occupying a core identical in size and shape with the sample core. The relative densities, α , of the diluted driver cases in the spherical and cylindrical cases are very similar, being 0.619 and 0.614, respectively.



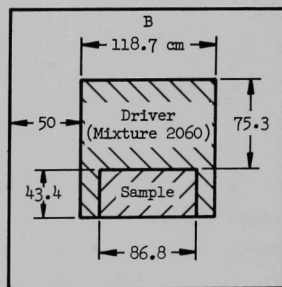
Case VI



Case VII



Case VIII



Case IX

Notes:

$$\alpha = \frac{\text{Density of Driver as Used}}{\text{Maximum Density Obtainable}}$$

Dimensions in cm

Compositions as in Tables II and IV

Fig. 4. Cylindrical Zoned Criticals and Their Equivalents

Case VIII is the analogue of Case III. The length-to-diameter (L/D) ratio of the sample volume is unity, and the dimensions are chosen to use 200 kg of plutonium. However, since the system is made critical by adjustment of driver length, the critical reactor has an overall L/D ratio near, but not exactly equal, to unity. In the case of the eccentric sample, Case IX, adjustment to criticality is again made through alteration of driver length, although the resultant L/D ratio is extremely near to unity in this particular case.

Table X shows critical masses and one-group cross sections for the four cylindrical reactors studied with CRAM. Only five groups were employed, but appropriate weighting spectra were used in each region for condensing from the 16-group 635 Library in the manner adopted by Moorhead⁽¹³⁾ in his study of an oxide reactor.

Table X

CALCULATED PROPERTIES OF CYLINDRICAL ZONED CRITICALS
AND THEIR EQUIVALENTS
(YOM 16-group cross sections condensed to 5)

	VI	VII	VIII	IX
Mass of U ²³⁵ (kg)	516	745	201.6	101
Mass of Pu ²³⁹ (kg)				
Central Point				
U ²³⁸ σ _f	0.0469	0.0557	0.0469	
Pu ²³⁹ σ _f } (b)	1.916	1.874	1.914	
B ¹⁰ σ _α	1.815	1.533	1.805	
Eccentric Point				
U ²³⁸ σ _f	0.0462	0.0543		0.0465
Pu ²³⁹ σ _f } (b)	1.919	1.877		1.923
B ¹⁰ σ _α	1.834	1.559		1.800

The eccentric point is 1.8 cm from the principal axis of the cylinder at a point 17.1 cm from the blanket-core interface.

The significant point is that the one-group cross sections in the all-sample reactor are very close to their values in the zoned reactor both for central and eccentric sample positions. However, for the most accurate work, it is necessary to calculate a correction, if only to show that it is small. The uncertainty in this calculated correction would have to be very large if it were to be comparable with the experimental error of an actual measurement.

In this connection, the relevant comparison is that of the one-group cross sections in the different cases calculated by use of the same library and the same model. The differences between these one-group cross sections and those obtained by DSN calculations in spherical geometry are greater.

Perturbation Worths at Central and Eccentric Positions

The situation becomes less satisfactory when we turn to perturbation effects, the difference between values in the all-sample cylinder and in the equivalent position in a zoned arrangement being greater. Numerical results are given in Table XI. We may regard the differences as arising from two separate components: the perturbation numerator, which is a function of the fluxes and of the perturbing specimen, and the denominator, which is a function of the fluxes and the material of the reactor. If we normalize through use of CRAM-computed values for the denominator, we find that the difference between the numerators is increased, not diminished, and reaches values of several percent.

Table XI

CENTRAL DANGER COEFFICIENTS EXPRESSED IN % PER gm-atom
AND THE PROMPT NEUTRON LIFETIMES

	VI -	VII	VIII
U ²³⁸	-0.00399	-0.00268	-0.00386
Pu ²³⁹	+0.0829	+0.0598	+0.080
B ¹⁰	-0.0358	-0.0318	-0.0349
Perturbation Denominator	40.225	33.344	39.06
$\tau(\mu\text{sec})$	0.383	0.449	0.407

Since perturbation effects are sensitive to both flux and adjoint, and a specimen normally contributes positive reactivity effects due to some mechanisms, and negative due to others, greater percentage differences between perturbations in all-sample and zoned systems might be expected. This is particularly true for those cases in which the net perturbation effect is the small sum of large positive and negative components.

The prompt-neutron lifetime is a number which can be measured by interpreting experimental observation in terms of a rather simple model, but is calculated zone by zone in terms of volume-averaged quantities. It is, therefore, not obvious how one can use a measured prompt-neutron lifetime in a zoned system to infer its value in an all-sample system other than by extrapolation from a number of measurements in different systems with graded sample sizes. The measurement and significance of measurements of prompt-neutron lifetime in zoned systems has been discussed by Brunson and his co-workers,⁽¹⁴⁾ who point out how two lifetimes can be inferred from measurements, one appropriate to each zone, but only in the case where these lifetimes are very different. Where there are separate zones with similar lifetimes, some form of average is extracted from experimental

data by a theory which ignores the dissimilarities in the zones. The CRAM code yields "core" lifetimes and "blanket" lifetimes typically different by a factor of 3 in the cases studied.

Perturbation Effects at Eccentric Positions

The CRAM output compiler enables the computation of perturbation effects at eccentric positions. Such calculations were made for the cases studied. The method used is subject to error near interfaces, particularly with large mesh intervals, and graphical smoothing of points was adopted, although with relatively few points this is a somewhat subjective operation. The results are shown in Table XII, where the third figure in the numbers quoted is hardly significant. The general inference to be drawn is as before, that although the agreement is within a few percent, calculations do not yield an accurate value for the correction term. It seems likely that this can be improved, but it is worth noting that if the calculational method is inadequate, an experimental method is of little value in checking cross-section data. On the other hand, a good calculation method simultaneously makes good experimental data valuable and an adequate calculation of small correction terms possible.

Table XII

PERTURBATION WORTHS (% per kg-atom) NEAR THE PRINCIPAL
AXIS OF ZONED AND ALL-SAMPLE REACTORS

Reactor	Z =	10 cm	20 cm	30 cm	Perturbation Denominator
VI	U^{238}	9.00	17.3	26.2	40.225
IX		8.00	17.5	25.3	38.403
VI	Pu^{239}	26.8	44.0	59.5	40.225
IX		26.8	42.5	57.0	38.403
VI	B^{10}	11.2	18.0	25.4	40.225
IX		11.1	18.5	25.8	38.403

Z is the distance in cm from the lower blanket-core interface at a point 1.9 cm from the central axis.

IX. CRITICAL MASS

From a homogeneous critical assembly, the quantity most accurately known is the experimental critical mass, which requires a knowledge only of fuel mass and isotopic composition. This simple number is not

available from a zoned critical array. However, this loss of the most accurately known quantity is less severe than might at first appear, for two reasons. Firstly, the heterogeneous, geometrically irregular critical mass of experiment must be converted to a homogeneous simple-geometry equivalent, and the precision of the former quantity is somewhat masked by the uncertainty of the correction term. Secondly, it must be assumed that cross-section errors compensate in some measure when a prediction of critical mass is made. To unravel these numbers requires the use of several experimental numbers, and a knowledge of only one of these to high accuracy, is of limited value.

X. OPERATIONAL CHARACTERISTICS OF ZONED ASSEMBLIES

The zoned-system approach outlined earlier has certain operational implications. For example, the average density of the core has been treated as a variable. The method of varying density is by the use of perforated pieces, and the availability of a range of these in several different diluent materials will make fairly fine average density changes possible, although probably tedious. The driver compositions envisaged have a fairly high stainless steel content, and pieces of this material are assumed to be available at different average densities. Low-density pieces are already used for special purposes. For example, the ZPR-III inventory includes perforated aluminum pieces with average densities of 50 v/o and 66 v/o. With 10 columns of stainless steel per drawer, and three or four types of stainless steel piece, a large range of values of void can be introduced whilst preserving one single drawer as the basic unit of the assembly.

The use of cores with substantial void has implications as regards safety, at least so far as the magnitude of a destructive explosion is concerned. The greater the voidage in an exploding core, the greater the energy release, since a given mass of material must reach a higher energy density before it generates sufficient pressure to blow the core apart. Some 7-10% voidage is unavoidable in a ZPR-III-type assembly, and the present proposals envisage percentage voidages two or three times as great in the driver region. It is prudent, therefore, to accept a possible increase in the size of a destructive burst although the presence of aligned holes giving short, easy flow paths for uranium vapour from regions of higher to lower importance may have an opposite effect.

It is not clear whether voidage in the core significantly increases the likelihood of having a destructive burst in the first place. There is, in a voided core, more opportunity for the fuel to compact if it once becomes molten, and less thermal capacity to chill it as it moves. If therefore, a limited reactivity addition of a quite specific amount is postulated, it may be found that compaction followed by a destructive burst results for a voided core, but not for a nonvoided core. The argument is not a convincing one,

however, particularly since similar qualitative arguments can be advanced suggesting that in certain specific circumstances the voided core is safer. For example, the presence of easy horizontal flow paths through the core may affect the way in which molten fuel slumps, making a compacted core less likely.

The use of zoning in itself, apart from the introduction of voidage, is a safety feature. Air-borne plutonium is a greater hazard than air-borne uranium at the same concentration, but the fact that the total mass of plutonium in a zoned system is a few times smaller than in an all-plutonium system is hardly significant. However, the metallic plutonium at present used in ZPR-III is canned, and because of clearance spaces in the can, its thermal expansion contributes very little in the way of a (prompt) negative temperature coefficient. The enriched uranium, on the other hand, is uncanned and does contribute a prompt negative effect, so that the use of this material in a zoned critical does preserve this valuable feature at least to a certain extent. Further, if an appreciable proportion of the fission takes place in U^{235} , the reactivity margin between prompt and delayed critical (β) is increased.

XI. CONCLUSION

A procedure has been outlined for designing a zoned critical which is optimum, within the limitations of certain assumptions. Closeness of spectral match between sample and driver is an important criterion of excellence, and this can be defined in various ways, emphasizing, if required, closeness of match in the low-energy part of the spectrum. This might well be done if a Doppler measurement in the zone were of principal interest.

It seems likely that one or more zoned criticals can give nearly all the useful information which might be derived from a full-scale critical of sample material without significant loss of experimental accuracy. Critical mass is excluded from this statement, and substantial computations may be necessary to calculate correction terms in other cases.

This report confines itself to showing how a zoned critical approach can give the experimenter nearly all the data he would obtain from a full-scale critical if he had sufficient plutonium available to build one. The use of that data in refining cross-section data for plutonium is another matter.

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